THE RECORD-BREAKING COLD WAVE OF MID-NOVEMBER 1955 IN THE NORTHWEST

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1. INTRODUCTION

A record-breaking cold spell hit Montana on the 11th of November and spread westward and southwestward through the Plateau, persisting in severity for a week, November 11–18, 1955, and causing heavy losses in unharvested crops and produce in unheated storage. At Helena, Mont. the temperature remained below 0° F. for 138 consecutive hours. After this period the cold air pushed into eastern sections causing near-blizzard conditions in the northeastern Plains and Lakes region and producing cold waves as far east as the Appalachians. This very cold air was eventually responsible for the first general snow in the Northeast and the great contrasts in temperature it provided as it lay over New England on the 19th and 20th helped to spawn a most severe storm off New England.

It is frequently the case that when unusually severe cold persists near one coast, the opposite extreme may occur near the other. This is due to the fact that below normal conditions are usually associated with abnormally deep persistent troughs aloft, while above normal conditions are associated with persistent ridges aloft. The distance normally found between long-wave troughs and ridges is such that a trough over the Plateau will accompany a ridge over the East and vice versa. During the period of the situation to be studied the 500-mb. heights in the Northwest were below normal by record amounts, while in the East they were 200 to 400 ft. above normal. Thus while much-below-normal conditions developed in the Northwest in mid-November, temperatures rose into the 80's in the East producing such late-season record high temperatures as 81° F. at Huntington, W. Va., 79° at Cincinnati, Ohio, and 78° at Baltimore, Md. This marked warming in the East, in contrast to the extreme cold in the West, set up ideal conditions for cold waves in the East also, when conditions finally became favorable for the cold air in the Northwest to move eastward en masse.

The cold Arctic air poured initially into Montana on the 11th causing one of the most severe cold spells in history for so early in the season. By the 13th it had produced subzero minima from North Dakota westward through the northern border States to northeastern Washington. Subfreezing minima occurred along the northwest coast and southward into California's Central Valley killing tender vegetables and unharvested grapes.

On the 15th many stations reported record low temperatures for so early in the season, e. g., −29° F. at Helena, Mont., −11° at Spokane, Wash., −3° at Boise, Idaho, and −9° at Ely, Nev. On the same day Portland, Oreg.,

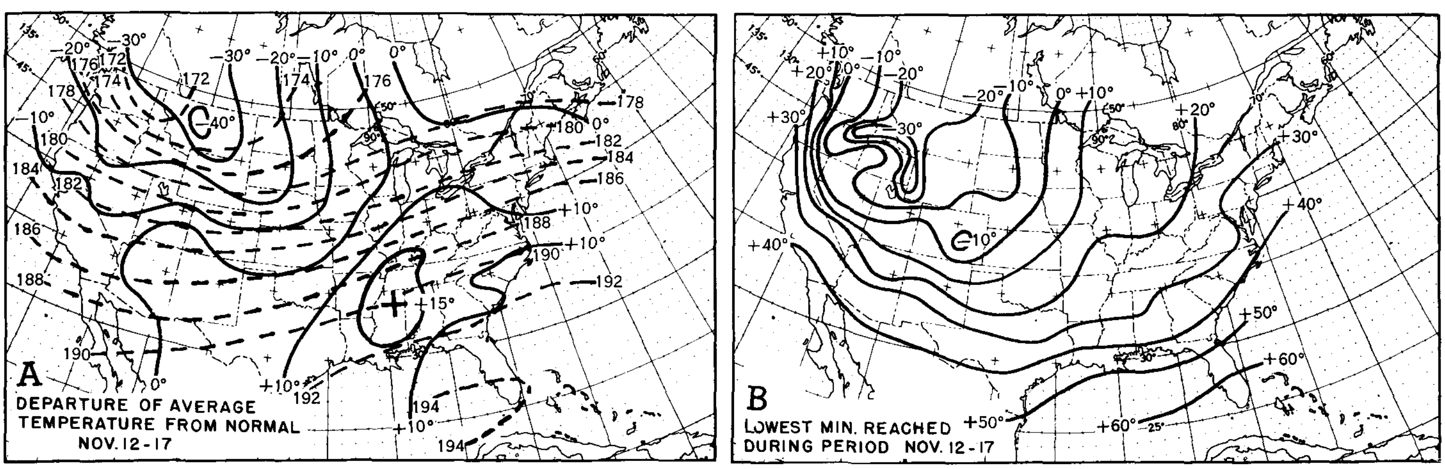

FIGURE 1.—Chart A shows departures of average surface temperatures from normal, November 12–17, 1955 inclusive (solid lines) and mean 500-mb. height contours (dashed lines) labeled in hundreds of feet. Chart B gives lowest temperature minima reached during same period.

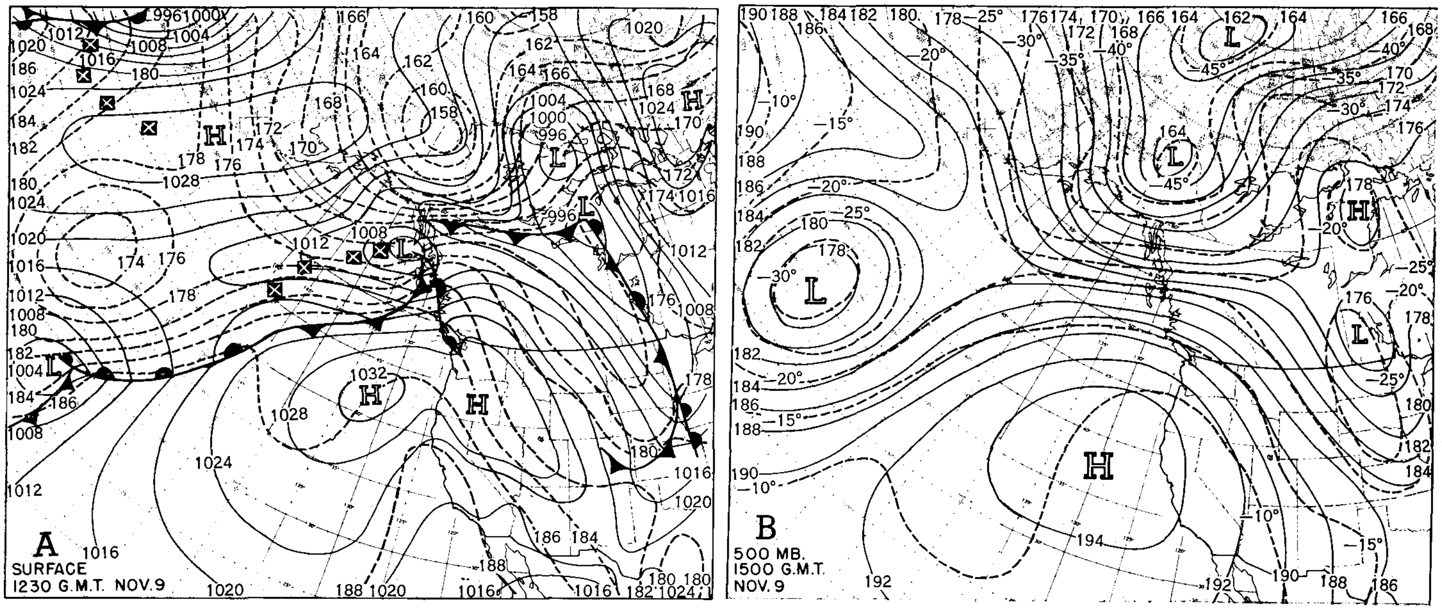

FIGURE 2.—(A) Surface chart and (B) 500-mb. chart on November 9, 1955. On surface chart 1,000–500-mb. thicknesses (dashed lines) are labeled in hundreds of feet. Previous 6-hourly positions of centers are indicated by "X". On 500-mb. chart isotherms (dashed) are labeled in °C. and height contours (solid) in hundreds of feet. Flags on wind shafts represent 50 knots, full barbs 10 knots, and half-barbs 5 knots.

reported a record early-season low of 13° as subfreezing minima extended southward along the coast to Eureka, Calif. At Salt Lake City, Utah, a −14° F. low on the 16th was 14° lower than ever before recorded during November. The average temperature on this day was 1°, or 38° below normal, the greatest daily departure ever recorded at Salt Lake City during any month. In Washington it was the longest severe cold spell on record for November, with Astoria having 135 consecutive hours below freezing. Wyoming experienced average temperatures nearly 25° below normal with several stations in the Yellowstone Basin reporting average temperatures near or below zero. Farther east Nebraska had the coldest mid-November weather since 1940. St. Joseph, Mo. had the coldest November on record with 10° F. on the 16th a new daily record. Figure 1A gives the departures of average surface temperatures from normal during the period November 12–17 with the mean 500-mb. flow superimposed. The 40° below normal in Montana for the period strongly contrasts with the 17° above normal in the Southeast. Figure 1B gives the lowest minima reported by each station during this period.

The protracted nature of this cold spell makes it convenient to divide the period into three parts. The initial phase embraces the first surge of cold air into the Northwest on the 11th and 12th, the middle phase covers the period during which the cold Low aloft performed a loop and came back to its starting point over northeastern Washington, and the final phase starts with the 15th as the upper Low and the associated cold dome moved out of the Northwest.

It will be seen that this cold spell was not characterized by abnormal surface anticyclonic conditions but rather was due to the persistence of an abnormally cold Low at upper levels. The thickness of the air column directly under the upper low center between 1,000- and 500-mb. pressure levels was generally 1,400 to 1,600 ft. thinner (21° to 24° C. colder) than normal for almost a week. Such a deep layer of cold air had an important bearing on the extreme surface temperature anomalies observed, since the thickness of an isobaric layer is directly proportional to the mean temperature in the vertical.

It is our purpose to study and record some of the synoptic aspects of the situation which produced such a record-breaking cold spell both as to intensity and duration at such an early date. It is also planned to examine some details of the vertical structure of the cold dome.

2. ANTECEDENT CONDITIONS AND PROGNOSTIC INDICATIONS

Figure 2A shows the conditions at the surface at 1230 GMT, and figure 2B shows the 500-mb. picture at 1500 GMT on Wednesday, November 9, about 36 hours prior to the first penetration of cold air at the surface into Montana. At this time there was a cold core of somewhat less than 15,800 ft. (fig. 2A) in the 1,000–500 mb. thickness field over Alaska. This is equivalent to a mean temperature of −36° C. in the column of air below the 500-mb. Low. A weak wave cyclone was just entering the coast at the surface about 600 miles south of the upper Low, in such a way relative to the upper contours that it was approaching the delta or exit region of an upper confluence pattern.

Accordingly, most forecasters would look for at least some deepening of the surface storm, not only because of the contours aloft, but because the wave cyclone would be approaching an area in the lee of the Continental Divide

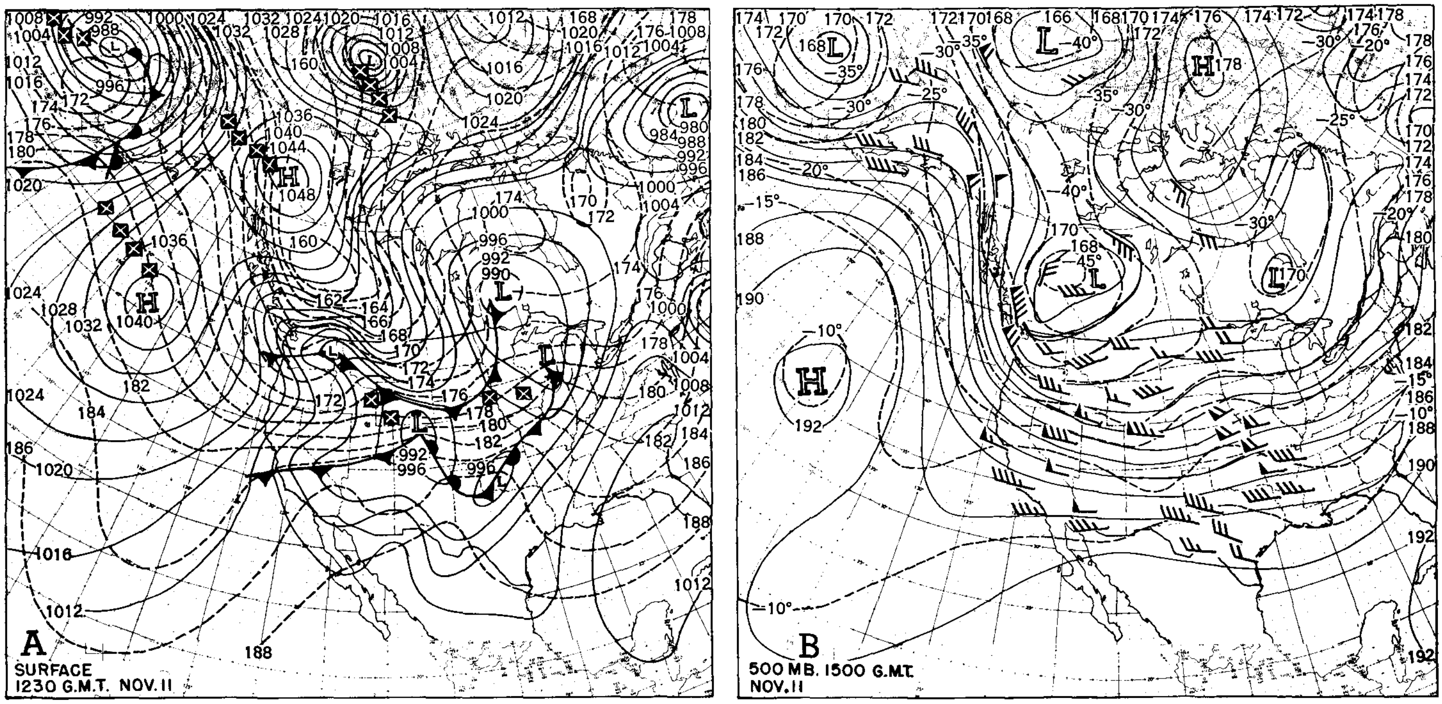

Figure 3.—(A) Surface chart and (B) 500-mb. chart on November 11, 1955.

which is normally divergent. However, in order for the wave to deepen enough to produce appreciable cold advection to its rear, while moving parallel to the upper flow, the upper heights would have to fall simultaneously. A southeastward movement of the upper Low and its associated cold core from Alaska would thus tend to result. Therefore, it seems clear that upper heights would have to fall over southwestern Canada if these effects were to be realized. No height falls aloft had been in evidence prior to this time which could be extrapolated toward southwestern Canada. Thus, the signal that the cold Low aloft was about to plunge southeastward into Washington State, Idaho, and Montana, was certainly not clearly in evidence at this time. It should also be pointed out that in terms of large-scale phenomena the clue to the turn of events appears likewise elusive. There had been no sudden or abnormal deepening evident upstream or in fact anywhere over Asia prior to November 9 which could have dispersed eastward at the group velocity.

Computations of movement of the 500-mb. Low using grid methods of averaging the geostrophic flow around the vortex such as the Wilson [1] adaptation of the Riehl-Haggard method, failed to indicate the nature of the ensuing development also. As can be readily guessed by merely looking at the November 9, 500-mb. contour pattern over Alaska and environs in figure 2B, the existing momentum would carry the Low east and northeast.

In fact 24 hours later a filling Low center northeast of Aklavik, N. W. T., did verify the computation well. However the main 24-hour 500-mb. height fall plunged southeastward to British Columbia and increased in magnitude from 600 ft. over Alaska, to 1,000 ft. over British Columbia at 1500 GMT on the 10th. This 24-hour 500-mb. height fall area, in the subsequent 24 hours, again plunged south-southwestward across the initial contour pattern into Oregon to produce the 500-mb. pattern in figure 3B. Although the grid method did verify fairly well in 24 hours, it seemed to be a fortuitous result of residual low pressure in the verifying area, *while the developmental kinetic energy was actually plunging southeastward and southward*, propagating the height falls and the bulk of the cold dome with it. Of course it might be said that the grid method isn't expected to predict this aspect of what occurred since it should only work for barotropic or semibarotropic conditions. Actually most upper Lows are at least similarly baroclinic and even so respond moderately well to the mean flow around the periphery, so long as there are no environmental factors operating to change the peripheral mean flow. Of course, with such environmental factors operating, the longer the effects of the initial conditions are projected forward, the greater will be the error in the final result.

In retrospect however, the following clues, which were available on November 9, seem to take on added importance in explaining some of the changes in the peripheral circulation which produced the tremendous height falls over the northwestern States within 48 hours after the initial conditions pictured in figure 2:

(1) The major ridge at 500 mb. had retrograded in the previous two days from a position inland over eastern Washington. Furthermore, there had been persistent height rises in the Gulf of Alaska for at least 36 hours indicating rather strong anticyclogenesis was taking place.

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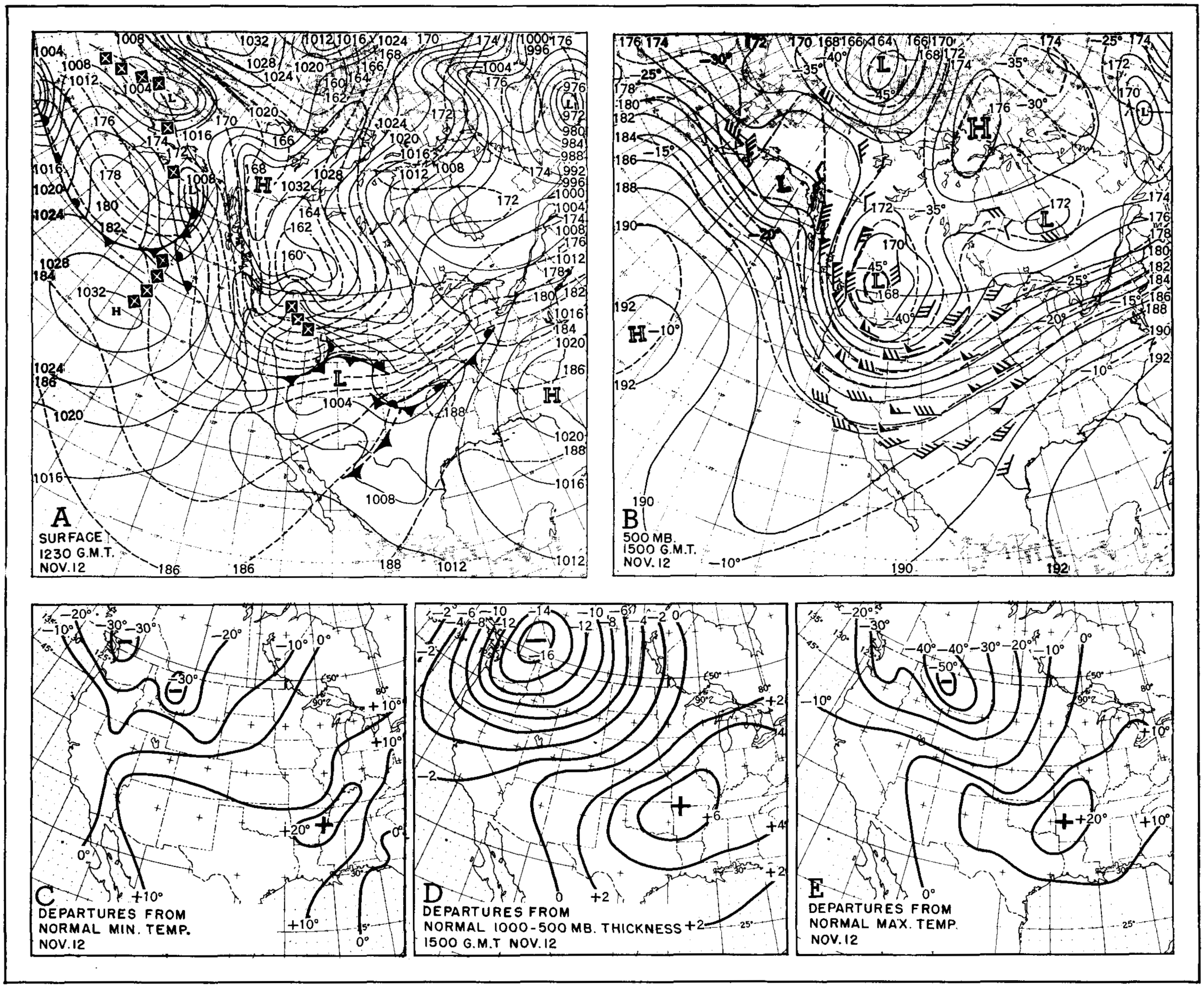

FIGURE 4.—(A) Surface chart and (B) 500-mb. chart on November 12, 1955. Chart (C) shows departures from normal of surface minimum temperatures in °F., and chart (D) shows departures from normal of 1,000–500-mb. thicknesses labeled in hundreds of feet, (E) departure from normal of maximum temperatures.

(2) Cold advection at 500 mb. was indicated toward southeast Alaska, tending to lower heights over southwestern Canada.

(3) Warm advection over the Bering Sea pointed to further height rises over western Alaska, which would serve to keep the gradient strong on the west side of the upper vortex. This would favor propagating the momentum of the northerly flow southeastward, as the gradient to the southeast weakened due to falling heights in that area.

(4) The fourth factor was the strong confluence zone at 500 mb. straddling the coast near 55° N. The entrance zone off the coast may be interpreted as an area of accumulation of air and the exit zone over southwestern Canada as one of depletion. This would tend to produce height rises and anticyclogenesis at the entrance and height falls near the exit of the confluence zone causing further retrogression of the ridge off the west coast allowing the Alaskan Low to plunge southeastward.

In addition to the failure of the grid method of computation, it should be pointed out that other auxiliary tools normally available for prognosis also did not indicate what was to transpire. One such tool, the advection of vorticity by the 500-mb. Fjørtoft [2] space mean flow (not shown) not only did not indicate what was to transpire, but in fact indicated that the vorticity would move to the northeast from Alaska. This is a common failing of the Fjørtoft method. It cannot forecast this important mechanism of plunging since this very process radically alters the space mean flow.

The hemispheric numerical barotropic prognostic similarly did not predict the penetration of the cold upper Low into the State of Washington. However no developmental virtues have been claimed for the barotropic prognosis. Neither did the baroclinic numerical prognostic predict this event but this is of course not surprising since the vorticity responsible for the development originated beyond the northwest boundary of the data network. The program employed assumes that the vorticity advection is zero at the boundaries. It may well be that the baroclinic prognostic would have predicted this event if the data network included the Alaskan area, but this has yet to be shown. Extended forecasting methods of predicting readjustments in large scale features also fell short of predicting the onset of this cold spell in the extreme Northwest, indicating indefinite or conflicting evidence in the large-scale features. It was not until 1500 GMT on the 10th that indications were sufficiently definite for this severe condition to be included in the NWAC 500-mb. prognosis for 0300 GMT, November 12.

Since the Gulf of Alaska region and the Yukon are favored sites for the generation of dynamic instability [3] with enormous effects on the weather over the United States within 48 hours, much more study must be made on this problem, and particularly in this area.

3. INITIAL PHASE OF THE COLD WAVE

By 1830 GMT on November 10 (not shown), an Arctic cold front at the surface was crossing the Canadian border and about to invade Montana, having moved southward in the rear of a deep (982 mb.) surface Low in Manitoba. This deepening had resulted from the weak surface wave cyclone which had crossed the coast of southeast Alaska on the 9th directly beneath the strong upper height falls plunging southeastward. By 1230 GMT on the 11th (fig. 3A) the surface Arctic air was well entrenched in the northwestern Plains while the 1500 GMT 500-mb. Low was centered over British Columbia (fig. 3B) with Prince George, B. C., reporting −45° C., indicating an abnormally cold upper vortex indeed. By this time 500-mb. heights had fallen in 48 hours almost 2,000 ft. at Seattle, Wash., while 1,000–500-mb. thicknesses were more than 1,400 ft. (21° C.) colder than normal in the vicinity of the upper vortex. This resulted in surface maximum temperatures in Montana on the 11th being 40°–50° F. lower than the previous day, with maxima in the north central areas not going above 10° F. At 500 mb. on the 11th (fig. 3B) the gradient over the northwestern States was very weak with average winds of about 30 knots, while the northerly current west of the Low was relatively strong, averaging 75 knots or possibly more.

By 1500 GMT, November 12 (fig. 4B) the upper Low had been propagated southward to the weak gradient area just north of Spokane, Wash., by the strong northerly jet along the coast of southeast Alaska and British Columbia. The 500-mb. temperature lowered to −43° C. at Spokane and 1,000–500-mb. thickness departures from normal increased 400–800 ft. from the previous day producing a departure of 1,600 ft. (24° C.) in the lower half of the atmosphere near northeastern Washington and northern Idaho.

This caused a further lowering of surface maximum temperatures over the northwestern States on the 12th. From the previous day's values of 10° to 20° F., maxima dropped to 0° to −10° F. in eastern Montana and into the 20's along the coast of Washington.

Figure 4C shows the departures from normal of minimum temperatures and figure 4E shows the departures of maximum temperatures in comparison with the 1,000–500-mb. thickness departures on the 12th (fig. 4D). The minima were 30° F. or more below normal while the maxima were 50° F. or more below normal at some areas in the Northwest. By the morning of November 13, minima ranged from 30° below zero at Cutbank, Mont., to near zero from the Dakotas westward through Wyoming and northern Nevada, except for the coastal regions. Seattle had a minimum of 13° F., the second morning the minimum dropped below 15°.

4. MIDDLE PHASE OF THE COLD SPELL

The contours around the Low near Spokane, Wash., at 500 mb. on November 12 (fig. 4B) exhibit considerable eccentricity (80-knot winds west of the center and 30 knots east of the center) suggesting that the maximum cyclonic vorticity would propagate toward the weaker gradient area to its east. This actually occurred but only in the form of a short-wave trough moving east-northeastward toward James Bay (southern Hudson Bay). At the same time a weak-appearing short-wave

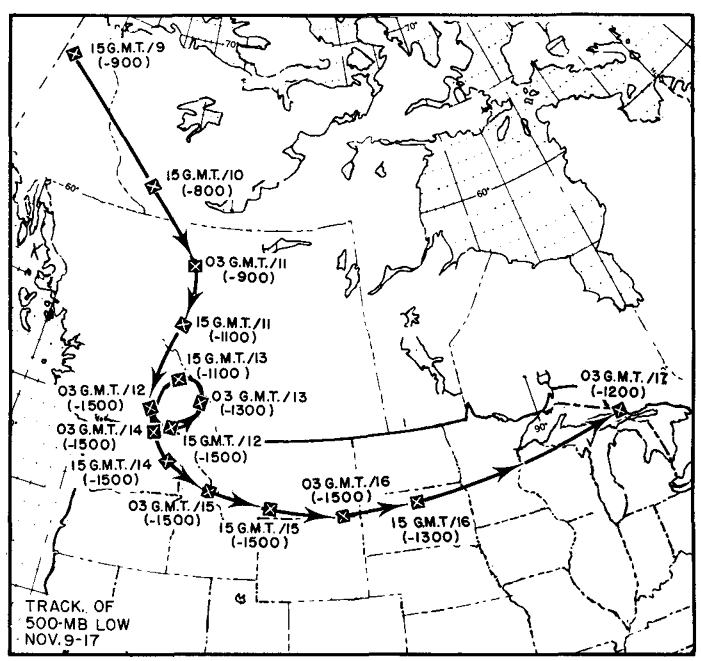

Figure 5.—Track of 500-mb. Low during period November 9–17. Date and time groups are separated by slants with departures from normal of central height values (feet) enclosed in parentheses. Successive positions of center at 12-hour intervals are indicated by "X".

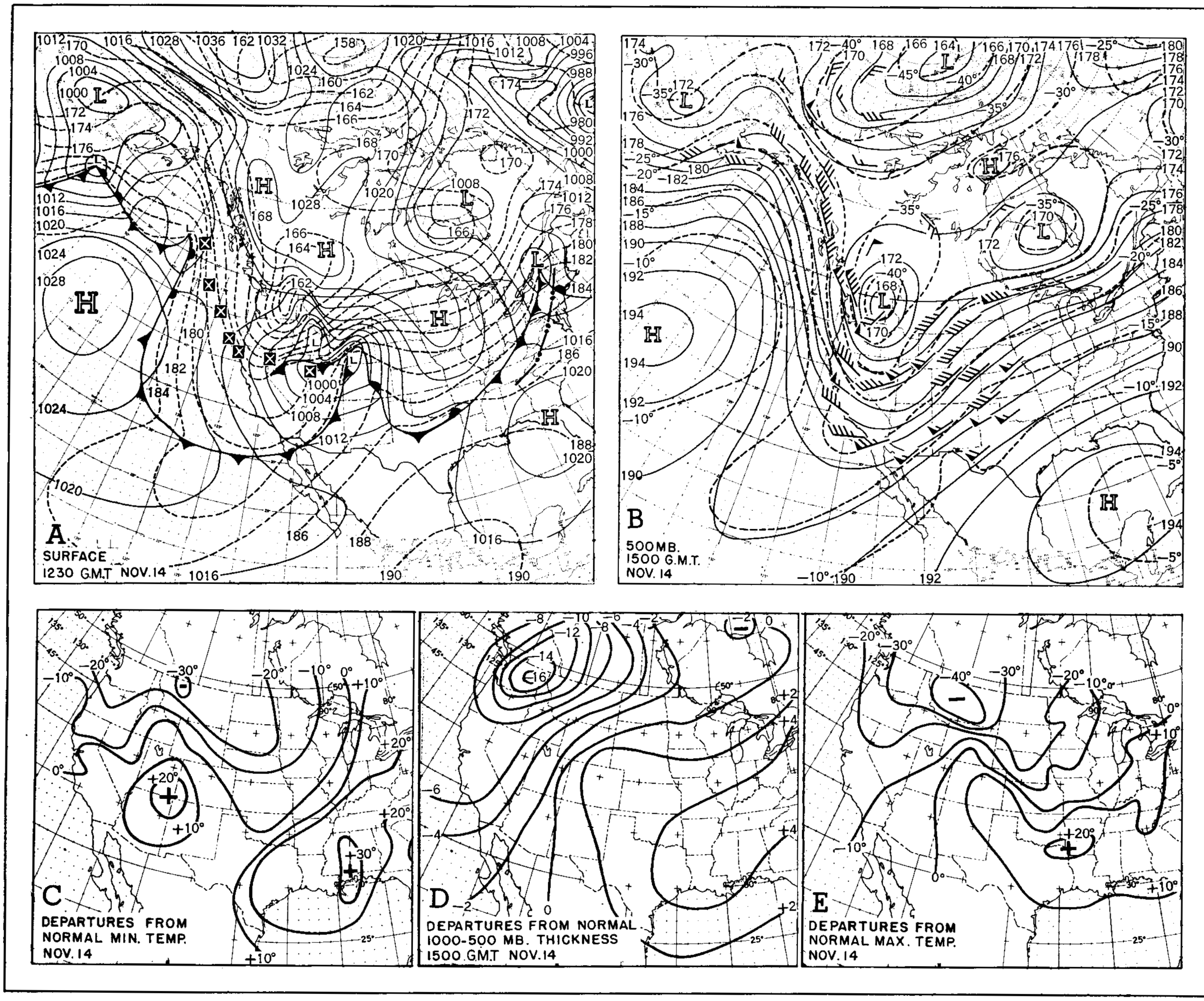

FIGURE 6.—November 14, 1955. (A) Surface chart, (B) 500-mb. chart, (C) departure from normal of surface minimum temperatures, (D) 1,000–500-mb. thickness departure from normal, (E) departure from normal of surface maximum temperatures.

undulation of the contours was rounding the long-wave ridge in the strong westerly current in the Gulf of Alaska, having resulted from a 24-hour height fall of 600 ft. in the ridge over this area. This perturbation was associated with a weak "A" (CIT) type Low [4] at the surface in the Gulf of Alaska (fig. 4A).

In the absence of such an approaching short wave, height rises probably would have occurred in the stronger gradient area to the west of the 500-mb. Low near Spokane, and the whole vortex would have moved eastward ending the cold spell in the Northwest. However the rapid southward translation of this minor feature down the east side of the long-wave ridge in the Gulf of Alaska introduced height falls into the west and southwest quadrants of the main upper vortex. The net effect on the main cold core circulation was to produce a small cyclonic trajectory to its center over British Columbia (fig. 5) together with its associated 1,000–500-mb. thickness anomaly, so as to return the cold core to northeastern Washington on the 14th. By this time the surface "A" type Low was in the central Plateau (fig. 6A) and the 1,000–500-mb. thickness departures were again more than 1,600 ft. (24° C.) colder than normal over Washington. The associated departures from normal of the surface maximum and minimum temperatures (fig. 6C and E) were thus very similar to those reported two days earlier. For example, below zero minimum temperatures were registered on the 15th in eastern Washington, Oregon, Idaho, Montana, Wyoming, northern Utah, and Nevada. Seattle had its lowest minimum of 6° F. during this phase of the cold spell. Ukiah, Oreg., a little south of Pendleton, reported a −32° F. minimum.

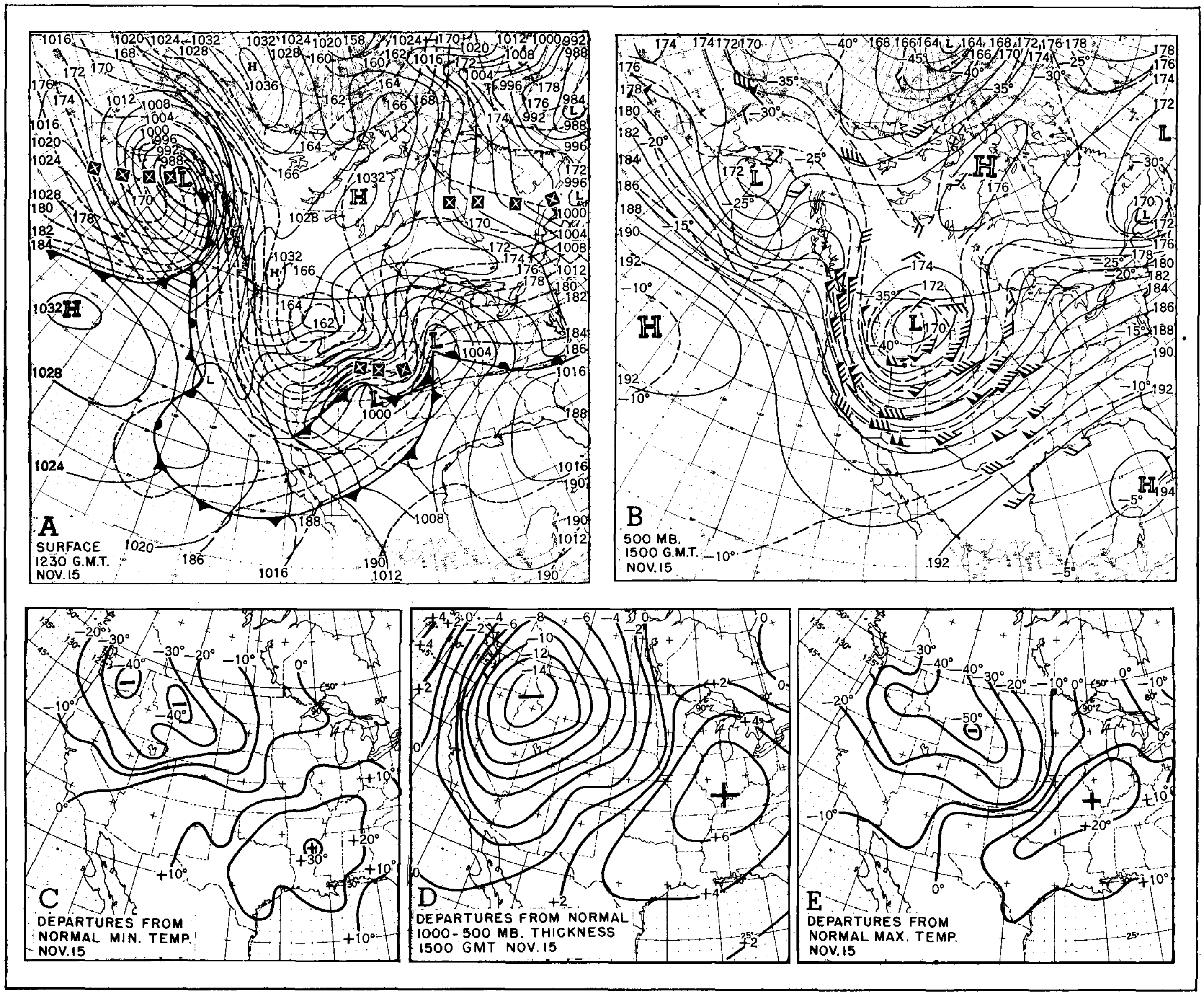

FIGURE 7.—November 15, 1955. (A) Surface chart, (B) 500-mb. chart, (C) departure from normal of minimum temperatures, (D) 1,000–500-mb. thickness departure from normal, (E) departure from normal of maximum temperatures.

The surface pressure pattern for 1230 GMT, November 14 in figure 6A has long been recognized as the type which precedes cold waves in Utah. In 1931, Hales [5] wrote that for a cold wave to sweep the Utah section of the Rockies, the center of the High must be placed well to the west of the Divide with a vigorous Low emerging from the coast of Oregon or Washington and passing to the southeast through southern Utah.

Such Lows are now generally referred to as "A" type Lows after I. P. Krick and R. D. Elliott who originally developed the CIT weather types [6]. A necessary concomitant of these storms aloft is a deep cold trough over the Plateau near 115° W. and a stationary long-wave ridge near 145° W. The first phase (day) of this type is when the Low breaks off ("skagerraks") in the Gulf of Alaska. In the current situation this was on the 12th. Average timing for this type requires that it be a deep storm near Moosonee, Ont., about 6 days later. The current analogue reached Moosonee on the 17th after passing across the Lakes as a severe storm.

Perhaps the most famous "A" type analogues of recent memory were those of January 1949. The maps of January 7–9, 1949, both surface and 500 mb., were very similar to the current situation from the 9th to the 14th. However there the similarity ends. For subsequent to January 9, 1949, the cold cyclonic core plunged south-southwestward to southern California, stagnating there for a few days and causing snow at sea level in the Los Angeles Basin. In the current situation the cold vortex behaved in a more conventional fashion.

To return to some of the more remarkable details of the November 1955, situation, the surface map in figure 6A

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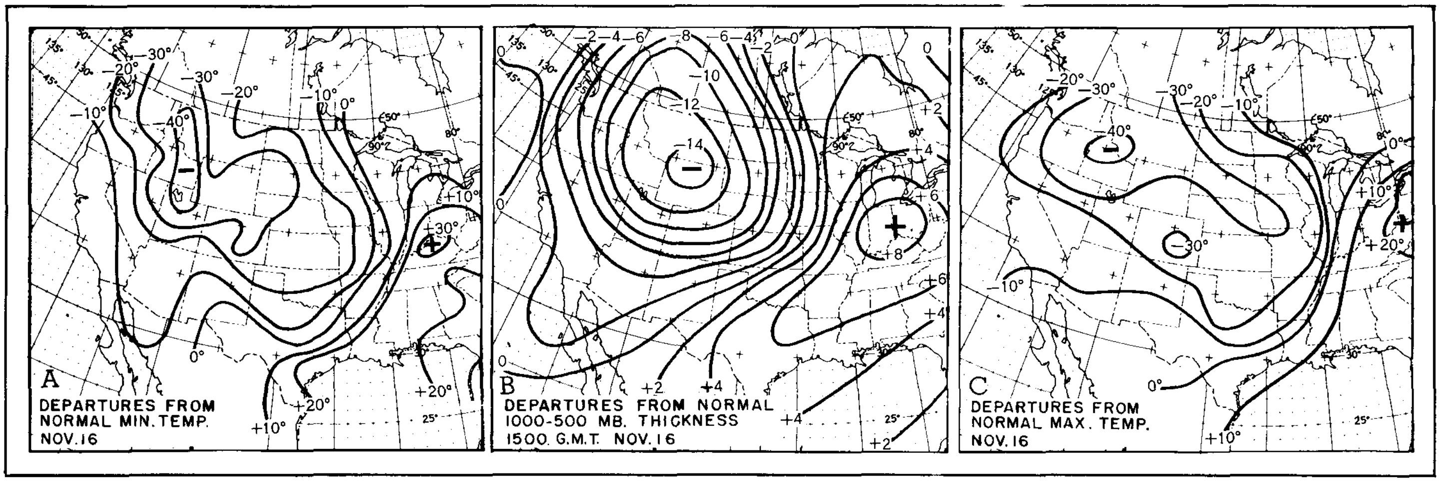

FIGURE 8.—Departures from normal of surface minimum temperatures (° F.) shown in chart (A), departures of 1,000–500-mb. thicknesses (hundreds of feet) in chart (B), and departures of surface maximum temperatures (° F.) in chart (C) for November 16, 1955.

over the Plateau shows the extremely cold core of 16,200 ft. in the thickness lines in eastern Washington, with the strong pressure gradient in the rear of the surface Low over Utah. This gradient intersected almost at right angles the strong gradient of mean temperature lines packed between the Arctic front extending west from the surface Low and the core of the cold air farther north.

Thus cold advection of a strength comparable to the most severe encountered even in mid-winter was indicated threatening Nevada and Utah and points east and southeast. As mentioned before, in the ensuing two days Salt Lake City experienced temperatures lower than ever before so early in the season and the greatest departures of average temperatures from normal ever experienced in its history.

The easternmost wave in the Gulf of Alaska on the surface chart of the 14th was not associated with any upper height falls and therefore proved to be a stable wave and not a new "A" type wave. It therefore had no bearing on ensuing developments.

5. FINAL PHASE OF THE COLD WAVE

During November 14 the cold vortex drifted slowly east-southeastward into southwestern Montana. Figure 7 shows conditions on the morning of November 15. At 500 mb. (fig. 7B) cold advection toward the relatively weak contour gradient was evident in the northern Plains suggesting this was an area of imminent height falls. The speed maximum in the peripheral jet was located in the southwestern quadrant of the upper Low. At the same time a strong westerly stream had developed from 42° to 50° N. along the meridian of ship "P", due to a strong 24-hour height fall of over 1,200 ft. just southeast of Kodiak. This picture clearly suggested large rises propagating into western quadrants of the upper Low in the Northwest in the ensuing 36 hours. Together with indicated height falls east of the Low, the upper Low moved rapidly eastward in response to this isallobaric field. At the surface (fig. 7A) the "A" type Low was well organized as a wave cyclone over Iowa, and the Arctic air at the surface was poised to push rapidly into the Plains. These circumstances contrasted sharply with the warm temperatures existing or expected over the eastern part of the country.

The departure from normal charts for the 15th show that maximum temperatures (fig. 7E) were in excess of 50° F. lower than normal in Wyoming contrasted with over 20° F. above normal from Ohio to Texas. Furthermore minima (fig. 7C) were 30° F. above normal in Arkansas that morning.

Thus on the 16th as the surface cold front moved eastward, severe cold waves occurred as maximum temperatures plunged 40° F. lower in the west central Plains than the previous day while they rose about 30° F. over Illinois and Missouri.

Figure 8 shows temperature and thickness departures from normal on the 16th. Thicknesses (fig. 8B) were more than 800 ft. above normal in Ohio producing maxima (fig. 8C) more than 20° F. above normal in the East, e. g., St. Louis, Mo. reported a maximum of 81° F. Below normal thicknesses of almost 1,500 ft. in Wyoming were associated with 30° to 40° below normal minima (fig. 8A).

The surface storm deepened rapidly as it moved from Iowa to Sault Sainte Marie, Mich., on the 15th and 16th due to strong cyclonic vorticity advection producing large height falls aloft moving rapidly eastward. This resulted in near-blizzard conditions with 2–9 inches of snow from the Dakotas to New England. On the 16th the cold wave edged toward the east coast and maximum temperatures from Missouri to northern Texas fell 40° to 50° below the previous day's values. By this time slow warming was in progress in the Northwest.

6. THE 500-MB. TEMPERATURES

The coldness of the vortex at 500 mb. during this period is very impressive, even though extreme temperatures for constant pressure surfaces are not yet available in published form. An older publication, "Extreme Temperatures in the Upper Air" [7] containing only very short records, shows that at 5 km. (about 16,400 ft.) the lowest temperature measured up to that time over the whole of North America was −51° C. in January over Alaska. For the continental United States the lowest value was −48° C., again in January, at Bismarck, N. Dak. and Sault Sainte Marie, Mich. The minimum at 5 km. over continental United States for November was −40° C. In the November 1955 situation, −48° C. was the lowest value reported when the Low was in northwestern Canada, while the continental United States stations reported 500-mb. temperatures as given in table 1 (for comparison the 500-mb. values for Nov. 1955 have been converted to 5 km. using a lapse rate of 3° C./1,000 ft. which is the value that prevailed at these levels during the current situation).

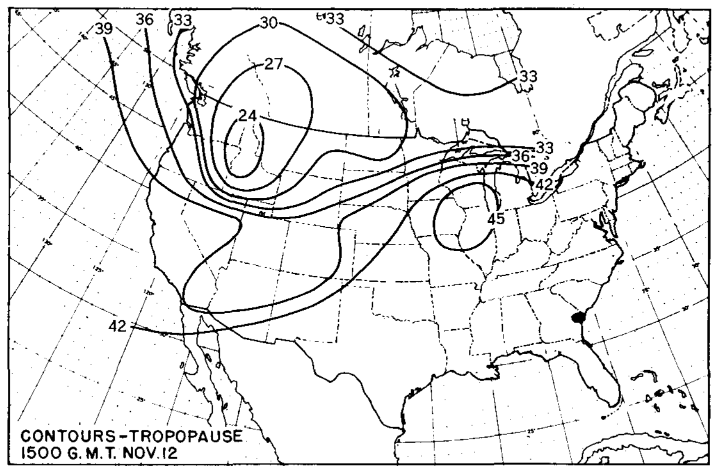

FIGURE 9.—Contours of tropopause at 1500 GMT, November 12, 1955, labeled in thousands of feet.

TABLE 1.—*Selected 500-mb. temperatures during cold wave in Northwest, November 1955, compared with previous records as tabulated in* [7]

Station	November 1955					Previous Record		
	500 mb.		Time GMT	Date	Temp. converted to 5 km.	Absolute Nov. min.	Absolute annual min.	Years of record
	Temp.	Height						
	° C.				° C.	° C.	° C.	
Spokane, Wash	−42	16,870	0300	12	−43	−38	−42	11
	−43	16,830	1500	12	−44			
	−41	16,710	1500	14	−42			
	−42	16,910	0300	15	−43			
Great Falls, Mont	−40	17,070	1500	12	−42	−36	−44	5
	−40	17,070	0300	13	−42			
	−38	17,030	0300	15	−40			
	−42	16,900	1500	15	−43			
Boise, Idaho	−38	17,200	1500	12	−40	−32	−36	5
	−38	17,090	0300	15	−40			
	−39	17,100	1500	15	−41			
Salt Lake City, Utah	−39	17,280	1500	15	−42	−35	−36	3
Glasgow, Mont	−41	17,140	0300	13	−43	−39	−41	2
	−38	16,970	0300	16	−40			
	−39	17,040	1500	16	−41			
Lander, Wyo	−38	17,100	0300	16	−40	Not available		
	−37	17,180	1500	15	−39			
Rapid City, S. Dak	−41	16,980	0300	16	−42	−35	−40	2
	−37	16,950	1500	16	−38			

From table 1 it can be seen that the upper-air temperatures at these stations were substantially lower than previous absolute minima as published in 1947, both for the month of November and even the year as a whole for some stations, particularly Salt Lake City, Utah, and Boise, Idaho.

7. THE STRUCTURE OF THE COLD DOME

In addition to its apparent record coldness throughout the troposphere the upper vortex possessed some other characteristics worthy of note. While perhaps not of record depth, it was nevertheless an unusually deep Low. The 500-mb. height was 1,400 feet lower than normal near the center during much of the period from November 12 to 17.

TROPOPAUSE ASSOCIATED WITH COLD DOME

It also possessed an unusually low tropopause, near or below 24,000 feet throughout most of its history, from Alaska on November 8 through its sojourn in the Northwest from the 12th to the 16th, retaining this same characteristic eastward to the North Atlantic. Figure 9 shows the tropopause topography at 1500 GMT, November 12. The nadir was somewhat south of the 500-mb. circulation center in figure 4B and seems to have been more closely associated with the vorticity maximum in extreme northeastern Oregon. A similar structure existed two days later at 1500 GMT on the 14th, at which time, as can be seen from figure 5, the Low was completing a loop in its trajectory prior to moving eastward into the Plains. Although drawn as a continuous surface in figure 9, there seems to have been a definite break in the tropopause between Bismarck and St. Cloud as indicated on the cross section in figure 10. The only significant tropopause at Bismarck and stations to the west over the cold dome had a potential temperature averaging about 310° A. This corresponds to the low Arctic tropopauses usually found over cold core Lows.

At St. Cloud there were two definite tropopauses in the sounding with the higher one at about 340° A. being the more significant. The less significant tropopause point was at about 310° A. and was therefore a diffuse continuation of the low Arctic tropopause. The higher point apparently was the same tropopause observed at 150 mb. at Green Bay, Wis., with a potential temperature of 365° A. It might therefore be inferred that the Arctic jet (to be discussed further below) from Salt Lake City to Rapid City at 300 mb. in figure 11 was located between Bismarck and St. Cloud in the region of the tropopause break, even though no wind reports are available between these two stations.

THERMAL PATTERNS AT 300 MB.

As can be seen from the cross-section in figure 10 the tropopause associated with the cold dome in the Northwest was well below the 300-mb. level at some stations. The thermal pattern at 300 mb. in the vicinity of the vortex associated with the tropospheric cold dome is therefore of some interest. This 300-mb. thermal pattern

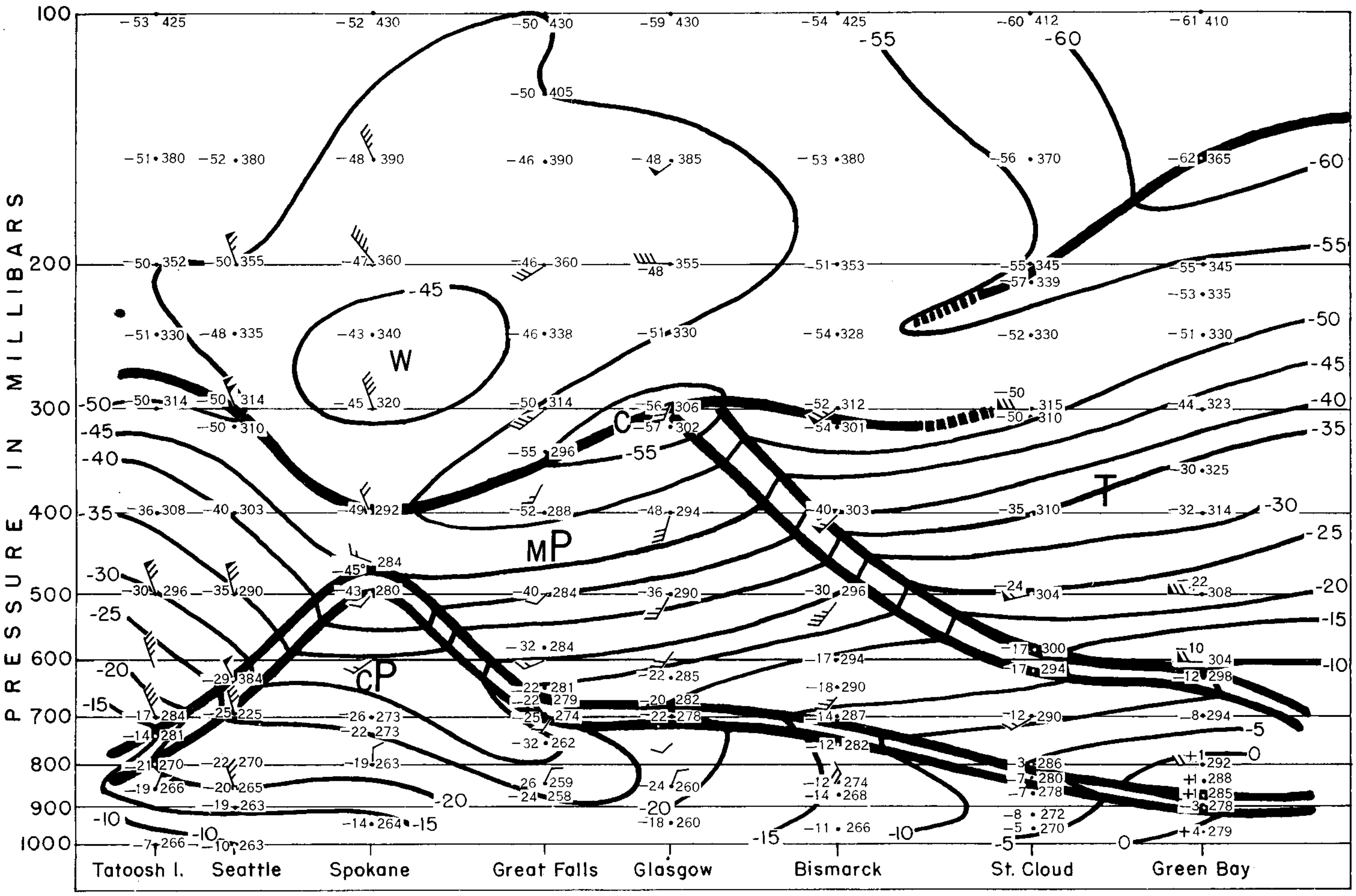

FIGURE 10.—East-west vertical cross-section through cold dome at 1500 GMT, November 12, 1955. Plotting model gives temperature (° C.) to left and potential temperature (° A.) to right. Wind force same as on 500-mb. charts. Double heavy solid lines are frontal zones, single heavy solid lines are tropopauses, and thinner solid lines are isotherms labeled in ° C.

(fig. 11) resembled in many respects the isotherms found by Kochanski [8] associated with stratospheric sinks at 300 mb. in midwinter of 1949. As figure 11 shows, a closed −45° C. isotherm over Idaho delineated the warm core of stratospheric air. This isotherm was practically congruent with the 24,000-foot contour in the tropopause topography. It was almost completely south of the −45°C. cold core at 500 mb. and the tropospheric cold core as represented by the 1,000–500-mb. thicknesses in figure 4A. Actually the warm core at 300 mb. seems to have been most closely associated with the cyclonic vorticity maximum rather than with the center of the vortex. This warm core was surrounded by a colder ring whose axis was along the tropopause intersection with the 300-mb. surface. The colder ring was delineated in the west, north, and east quadrants by the −50° C. isotherm which kinked in the vicinity of the tropopause intersection.

This type of analysis of the 300-mb. isothermal field in the vicinity of dynamic vortices at 300-mb. is standard procedure at the National Analysis Center because it seems to possess a high degree of reality as revealed by cross-sections and is a requisite for three-dimensional consistency.

Increased intensity of the stratospheric sink was evident on later maps when the upper Low was moving eastward through the Great Lakes. On the 17th the 300-mb. charts showed a warm core with an astounding −35° C. isotherm about 300 miles in diameter. Maniwaki, Que., reported −34° C., Buffalo, N. Y., −35° C., while winds of 200 knots in the associated jet axis were reported in close proximity to the south on the equatorward side of the cold ring

JET AXES ASSOCIATED WITH THE COLD DOME

The steepest slope in the tropopause topography from the Plains westward to the coast (fig. 9) was immediately to the north of a jet axis at 300 mb. (fig. 11). This jet axis appears to have been close to the 29,200-ft. contour of the 300-mb. surface. This is about 1,000 ft. lower than the jet associated with the polar front is normally found. It is now pretty well accepted that the location of the polar front jet axis is nearly vertically above the 18,400-ft. contour and the −18° to −20° C. isotherm at 500 mb. Assuming a temperature anywhere between −40° C. and −45° C. at 300 mb., any combination of these 500- and 300-mb. temperatures gives a 300-mb.

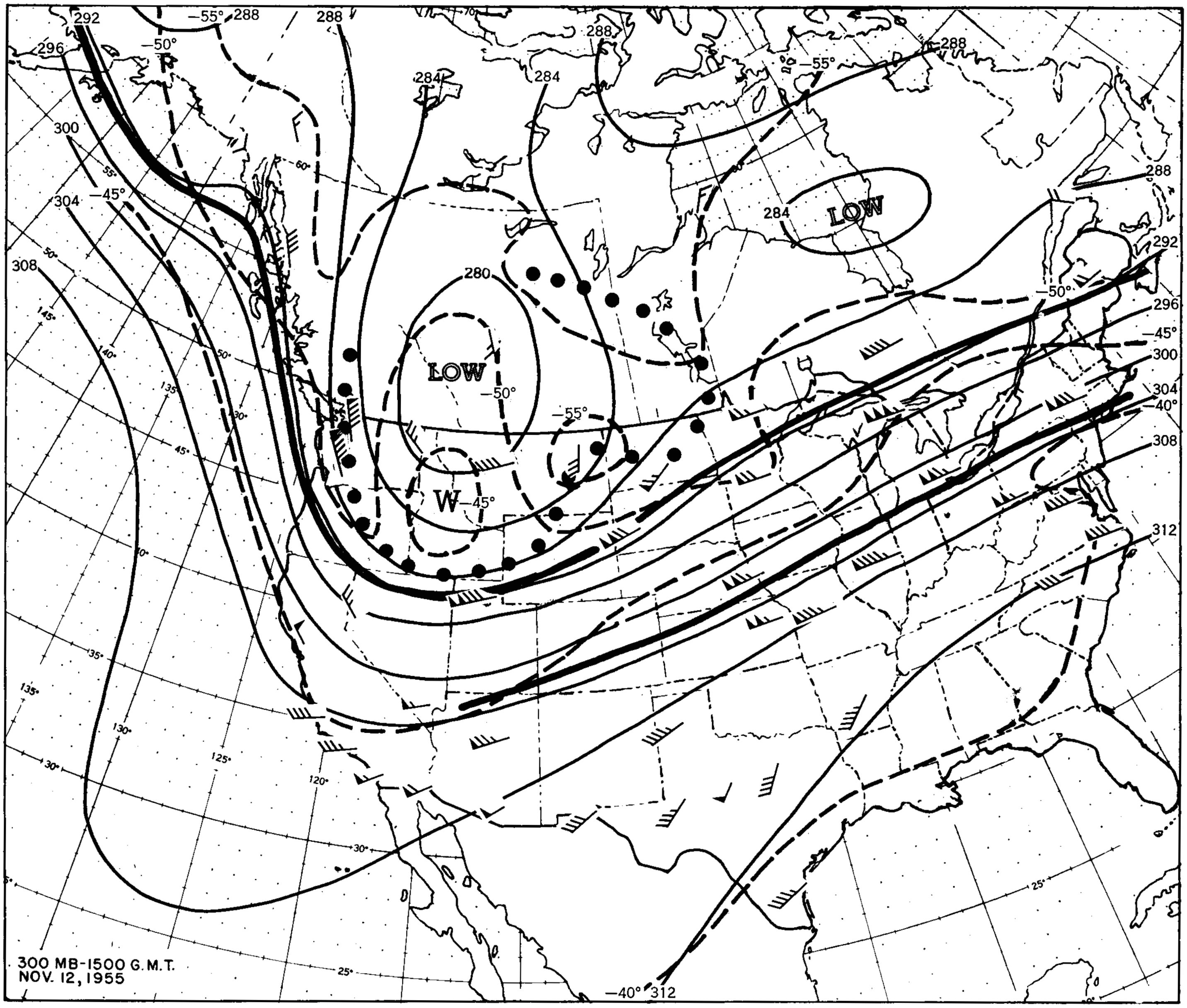

FIGURE 11.—300-mb. analysis above cold dome at 1500 GMT, November 12, 1955. Height contours (thin solid lines) are labeled in hundreds of feet. Isotherms (dashed) are labeled in ° C. Jet axes are heavy solid lines and tropopause intersection is dotted.

contour value of over 30,000 ft. directly above the 18,400-ft. contour at 500 mb. Experience with actual 300-mb. data suggests that the normal height for the polar front jet axis at 300 mb. may be near 30,300 ft. Over the southern Plateau in the current instance, neither the wind data nor the contour gradients suggested a well defined jet axis along the 30,300 ft. contour. This would tend to imply that the horizontal temperature field associated with the polar front was rather weak.

A glance at the thickness lines in Figure 4A shows comparatively little thermal shear in the vicinity of the 18,400–18,600-ft. thickness zone, this being one criterion of frontal intensity at the Analysis Center. By the same token the much stronger horizontal concentration of thicknesses between Salt Lake City, Utah, and Boise, Idaho associated with the Arctic front at the surface seems to have resulted in the secondary jet over the Plateau being the dominant one. This jet continued eastward along the 29,200-ft. contour (fig. 11) and apparently was associated with the main break in the tropopause between Bismarck, N. Dak., and St. Cloud, Minn., as discussed above

Although the polar front jet was weak and diffuse over the Plateau it apparently existed near the 30,300 ft. contour in greater intensity over the eastern sections of the United States due to the stronger baroclinic condition evidence in the 1,000–500-mb. thickness pattern. It also appears to have been well south of the tropopause break. As can be seen from the cross-section, figure 10, however, the polar front at 500 mb. was vertically below the tropopause break. The large horizontal separation between the 500-mb. polar front and its jet axis so much farther south over the Plains States is somewhat puzzling, but nevertheless seems to be a fact. It may have been due to an abnormal flatness of the frontal slope at upper levels.

FRONTS ASSOCIATED WITH THE COLD DOME

As discussed above in relation to the jet axes at 300 mb., the dominant baroclinic zone over the Plateau was north of Salt Lake City. The southern edge of this zone was near the 17,600–17,800-ft. thickness lines (fig. 4A). This southern edge is generally referred to as the Arctic front, i. e., the separation between cP and mP air. Figure 10 shows its vertical structure in east-west cross-section. It was characterized by a potential temperature of 282–284° A. This is in line with the value of about 286° A. suggested previously [9]. The cP dome reached a height of about 20,000 feet directly below the nadir of the warm Arctic tropopause, and was relatively shallow elsewhere. Figure 12 shows that this front was the most prominent feature of the air column at Great Falls, Mont., at 680 mb. and was also a significant feature at St. Cloud at 810 mb.

Another break showed up in the soundings in the vicinity of an even lower potential temperature of about 270° A., for example at 710 mb. at Great Falls and 910 mb. at St. Cloud. It also appeared in all soundings in the vicinity of the cold dome and is thought to represent the top of a much shallower stratum of real Arctic air, and was associated with representative surface temperatures below freezing. This discontinuity is rarely carried as a separate front in surface analyses since it represents merely a further intensification of the baroclinic temperature field associated with the secondary or Arctic front, and because it is of such limited vertical extent.

Above the cP dome as delineated by the Arctic front was a deep layer of mP air. Ordinarily, away from the proximity to a cold upper vortex the polar front is the vertical termination of the mP air. In the current instance however, at Great Falls, Mont., Edmonton, Alta., Spokane, Wash., and Boise, Idaho, the polar front was indistinguishable from the low Arctic tropopause; for example, in the Great Falls sounding at 350 mb.

The polar front is easily located on most soundings as a stable stratum whose top is at a potential temperature of about 298–302° A. or more, which is about the minimum potential temperature of tropical air in its source region. The east-west cross-section in figure 10 shows the polar front very prominently at Bismarck, St. Cloud, and Green Bay, Wis., at about 300° A. with the strongest vertical wind shear through this frontal zone. Above this frontal surface was a deep stratum of tropical air. From Glasgow west of Spokane there was no tropical air below the tropopause. As is evident in figure 12, the top of the mP

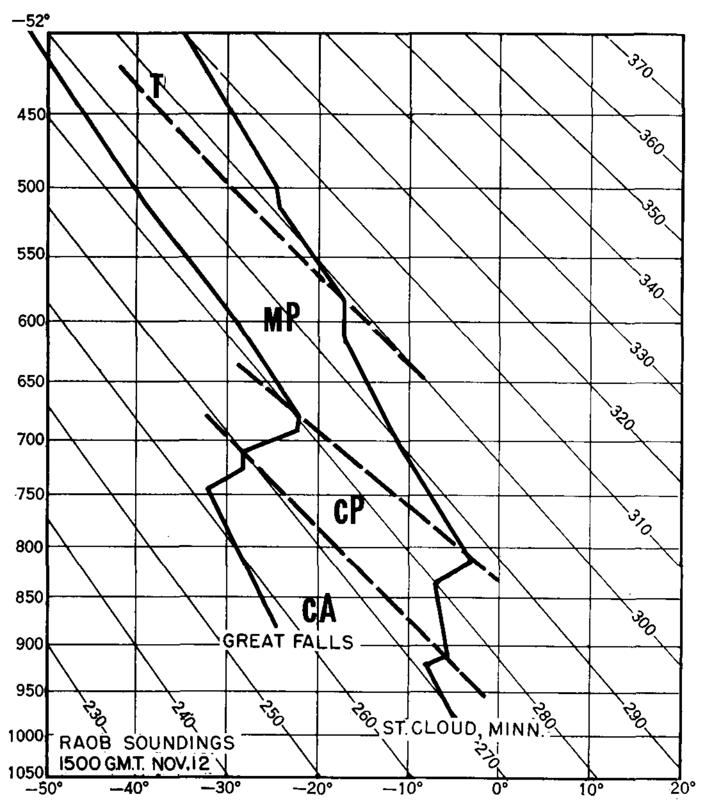

FIGURE 12.—Upper-air soundings for Great Falls, Mont., and St. Cloud, Minn., for 1500 GMT, November 12, 1955. Dashed lines indicate tops of frontal zones; slopes have no significance.

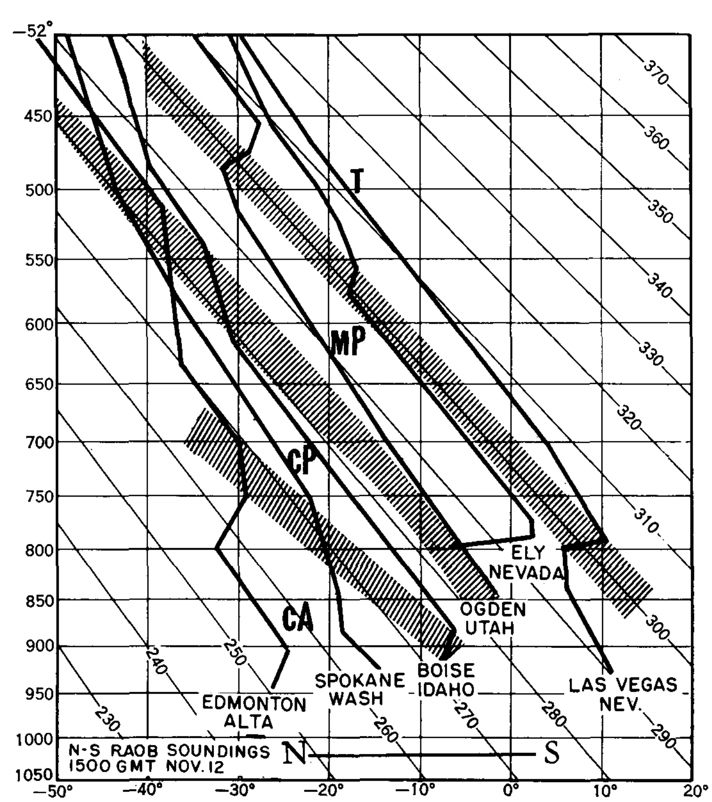

FIGURE 13.—Upper-air soundings on a north-south section through the center of the cold dome, at 1500 GMT, November 12, 1955. Sloping hatched zones connect frontal inversions in adjacent soundings. Slopes have no significance.

air was near 580 mb. at St. Cloud with tropical air above, while at Great Falls tropical air was clearly absent.

Figure 13 shows a series of soundings through the cold dome from Edmonton, Alta, southward to Las Vegas, Nev. The horizontal separation of the soundings on the pseudo-adiabatic chart has no relation to the geographical separation of the stations. The complex structure of the air masses associated with the cold dome is clearly evident. There were four distinct air masses in the vertical. Real Arctic air was at the surface at Edmonton and Spokane topped by an inversion surface at 270° A. This is not carried as a separate front in the surface analysis. Above the real Arctic air was a sloping stratum of cP air topped by an inversion surface evident at Boise, Spokane, and Edmonton with a potential temperature of about 285° A. This is the Arctic front in the surface analysis. Above this was a sloping stratum of mP air topped by an inversion surface at 300° A. Above this stratum was tropical air with potential temperature in excess of 300° A. This stratum was missing at Boise, Spokane, and Edmonton because of the low tropopause.

8. SUMMARY

1. It appears that dynamic instability associated with an unusual confluence in the westerlies normal to the coast of western Canada produced the retrogression which permitted a deep cold upper vortex to plunge southeastward from Alaska to Washington across more than 2,000 feet of height in 48 hours.

2. No current methods of prognosis successfully forecast this event nor even hinted at the readjustment in large-scale features of the circulation which occurred in the 48 hours subsequent to November 9.

3. Record-breaking surface negative temperature anomalies in the northwestern States were produced by the persistence of a dynamic cyclonic vortex over this area.

4. Record-breaking upper-tropospheric low temperatures maintained the deep cyclonic cold dome over this area by virtue of a continued flux of kinetic energy from the developing ridge upstream.

5. The strikingly warm core of stratospheric air at 300 mb. seems to have been most closely associated with the cyclonic vorticity maximum rather than with the center of the vortex, and was well south of the tropospheric cold dome.

6. In the south and east quadrants of the cold dome, tropical air was completely absent from the circulation in the upper troposphere within about 600 miles of the center due to the lowness of the tropopause.

7. A secondary jet associated with the baroclinicity of the Arctic front appeared to be the most prominent aspect of its upper peripheral circulation.

8. Despite the apparent homogenity of its tropospheric wind and thermal circulations, soundings through the cold dome clearly indicated sloping stratification of Arctic, continental polar, and maritime polar air masses within the inner core, with tropical air aloft no closer than about 600 miles.

REFERENCES

1. H. P. Wilson, "A Test of a Grid Method of Forecasting the Motions of Lows at 500 mb. in Arctic Regions," *Cir.* 2539 TEC 194, Meteorological Division, Department of Transport, Canada, Oct. 4, 1954.
2. R. Fjørtoft, "On a Numerical Method of Integrating the Barotropic Vorticity Equation," *Tellus*, vol. 4, No. 3, Aug. 1952, pp. 179–194.
3. J. Bjerknes, "Extratropical Cyclones," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 577–598.
4. R. D. Elliott, "The Weather Types of North America," *Weatherwise*, vol. 2, Feb.-Dec. 1949.
5. W. B. Hales, "Characteristics of Cold Waves in Utah," Utah Academy of Sciences, vol. 8, July 1931, pp. 115–124.
6. California Institute of Technology, Meteorology Dept., *Synoptic Weather Types of North America*, Pasadena, Dec. 1943.
7. U. S. Weather Bureau, "Extreme Temperatures in the Upper Air," *Technical Paper* No. 3, July 1947, 100 pp.
8. Adam Kochanski, *The Construction of 300, 200, and 100-mb. Maps of the Northern Hemisphere*, Dept. of Meteorology, University of California, 1950, 39 pp.
9. J. F. O'Connor, "Practical Methods of Weather Analysis and Prognosis," *NAVAER* 50-1P-502, U. S. Office of Naval Operations, 1952, pp. 18, 40.